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by C. Michael Hudson

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1965

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SUMMARY

The current state of knowledge of the effects of a vacuum environment upon fatigue is summarized in this report. The effects of temperature, pressure variations, prolonged exposure, and environment composition on fatigue life are discussed in detail. In addition, studies of the surfaces of specimens fatigued in vacuum are described.

to p. 14

Results indicate that fatigue life is better in vacuum than in air for most of the materials investigated. Most investigators attribute this increase in life to decreased oxidation of the material in the vacuum environment.

INTRODUCTION

[Data are presented for a number of materials, including some aluminum alloys, stainless steels and nickel-chromium alloys.]

2nd ¶

As space vehicles are scheduled for longer missions, they will be subjected to repeated loadings from a variety of sources, orientation adjustments, vibration of electrical and mechanical equipment, thermal cycling, and so forth. Consequently, the fatigue behavior of materials in a space environment will be of considerable interest to the spacecraft designer. One of the most important new parameters in this environment is the very hard vacuum that exists in space. The interaction of this vacuum with material surfaces may effect significant changes in the fatigue characteristics of these materials, since the initial stage of fatigue damage accumulation is generally understood to be a surface phenomenon.

The purpose of this report is to collate the findings of the various researchers and then define the current state of knowledge of the effects of a vacuum environment on the fatigue characteristics of metals. Towards this end, the literature was surveyed for reports on the subject of fatigue in vacuum. A modest number of papers were located, and the findings reported therein are reviewed in this report. The various mechanisms proposed to explain the differences between tests conducted in air and in vacuum are also reported.

A reference list is provided for those desiring to study the reported findings in greater detail. A bibliography has also been included listing papers pertaining to fatigue in vacuum which were not referenced directly.

SYMBOLS

The units used for the physical quantities presented in this report are given in both U.S. customary units and in the International System of Units (SI). (See ref. 1.) The conversion factors required for units used in the present study are presented in the appendix.

ϵ	maximum cyclic strain, percent
ϵ_p	maximum cyclic plastic strain, percent
N	number of cycles
N_3	fatigue life at a gas pressure of 760 torr (101.3kN/m^2), cycles
N_n	fatigue life at a nominal gas pressure of 1×10^n torr, cycles
R	ratio of minimum stress to maximum stress
S	maximum cyclic stress, psi (N/m^2)

SUMMARY OF FINDINGS

Early work in the field of vacuum fatigue indicated that the atmosphere had a significant effect upon the fatigue characteristics of metals. In 1932, Gough and Sopwith (ref. 2) presented experimental results showing that the fatigue life of copper and brass specimens was distinctly higher at a gas pressure of 10^{-3} torr (1.33 dN/m^2) than at atmospheric pressure. It was not until the mid-1950's, however, that a moderate number of programs investigating the effects of a vacuum environment upon fatigue life were begun. Since that time, these effects have been studied by an ever-increasing number of investigators.

Virtually all of the investigators substantiated the findings of Gough and Sopwith, that is, that a vacuum environment can significantly increase fatigue life. Most investigators attributed this increase in life to decreased oxidation of the material resulting from the fewer number of oxygen atoms present in the vacuum environment. The mechanism by which decreased oxidation increases fatigue life has not as yet been established, although a number of mechanisms have been proposed.

Additional findings included the discovery that:

(a) The fatigue lives of nickel-alloy specimens investigated at 1500° F (1089° K) tended to be longer in vacuum than in air at high strain levels, and longer in air than in vacuum at low strain levels.

(b) Water vapor was quite deleterious to fatigue life.

(c) In some instances, specimens tested after prolonged exposure to vacuum did not demonstrate as great an increase in life as specimens tested immediately after exposure.

(d) The exterior surfaces of specimens investigated in vacuum were visibly rougher, and contained more cracks than the surfaces of similar specimens investigated in air.

All the preceding findings and the mechanisms proposed to explain them are discussed in detail in subsequent sections.

The experimental results reported by various investigators are summarized in table I. Included in this table are the materials, types of loadings, pressure ranges, maximum stresses or strains, and other significant variables employed in the various investigations. The last three columns contain the ratios of fatigue life in vacuum to fatigue life in air N_n/N_3. The subscripts are used to define the nominal gas pressure at which the fatigue life was obtained. For example, the fatigue life at a pressure of 10^{-6} torr is represented by N_{-6}.

Completely reversed bending loadings were applied in almost all investigations because of the high strains which could be produced by reasonably low loads. The loads were generally applied by mounting the specimens between electromagnets and alternating the attraction of the magnets for ferrous blocks attached to the specimens. This entire apparatus can be installed inside the vacuum chamber; thus, the necessity of transferring the loads into the chamber from some external source is eliminated.

The majority of the research conducted to date has produced little information which is directly applicable to actual design problems. The materials investigated have, for the most part, been of academic interest only. In addition, unnotched specimens were used in a large number of investigations, whereas space structures will contain numerous stress concentrations such as rivets, welds, fillets, and so forth.

Variations of Fatigue Life With Pressure

The variation of fatigue life with gas pressure, in the range of 760 to 10^{-8} torr (101.3 kN/m^2 to 1.33 μN/m^2), has not been clearly established to date. In some instances, a continuous variation between fatigue life and gas pressure was found; whereas, in other instances, a stepped variation occurred. However, the fatigue life generally increased as the gas pressure decreased.

An example of continuous variation is shown in figure 1. In this figure, the fatigue life of pure copper, pure aluminum, and an aluminum alloy as a function of gas pressure has been replotted from references 3 and 4. Two possible mechanisms were proposed in references 3 and 4 to explain how the interaction of the environment and the material could produce this type of variation.

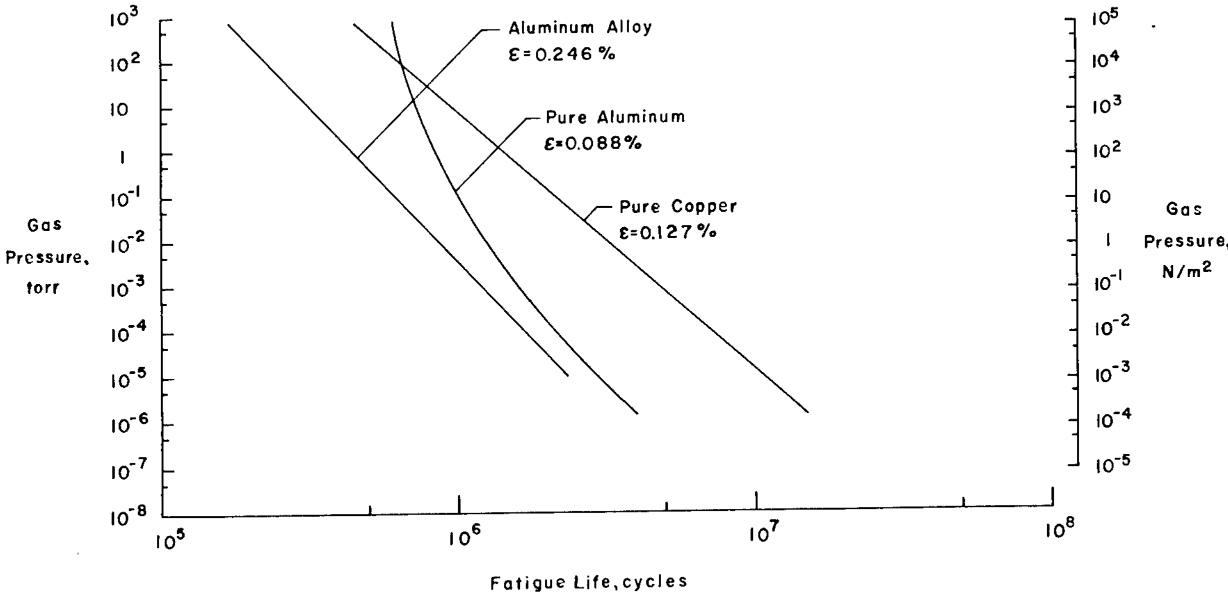


Figure 1.- Continuous variation between fatigue life and gas pressure (from ref. 3). R = -1.

One mechanism suggests that the oxygen molecules in the atmosphere combine with the atoms at the base of a fatigue crack, which weakens the material and, thus, accelerates fatigue crack growth. At a lower gas pressure, there are fewer oxygen molecules available to combine and weaken the material; consequently, the rate of fatigue crack growth is lower.

The second mechanism for explaining increased fatigue life in vacuum is based upon cold-welding behavior. Material studies have shown that two uncontaminated metal surfaces placed in contact and subjected to moderate compression will actually cold-weld together (ref. 5). It was proposed that at low gas pressures, the new fatigue crack surface developed under the tension loading is only partially contaminated because of the limited number of contaminating molecules available. During the compression portion of the cycle, the uncontaminated portions of the surface are brought back together under pressure and cold-welding occurs. The net effect is a delay in cracking and an extended life at the lower pressures.

In addition to Wadsworth and Hutchings (refs. 3 and 4), who proposed the preceding mechanisms, Snowden (ref. 6), in investigating pure aluminum; Kramer and Podlaseck (ref. 7), in investigating pure aluminum crystals; and Christensen (ref. 8) in investigating 2014-T6 aluminum alloy, found that fatigue life increased continuously with decreasing pressure. Other investigators have found a stepped variation between fatigue life and gas pressure. The curve plotted in figure 2 is an example of this stepped variation. This curve was derived from the results of tests on pure aluminum (ref. 9), and it shows that life was nearly constant from atmospheric pressure to 10^{-2} torr (1.33 N/m^2), increased steadily from 10^{-2} to 10^{-4} torr (1.33 N/m^2 to 1.33 cN/m^2), and was again nearly constant for lower pressures.

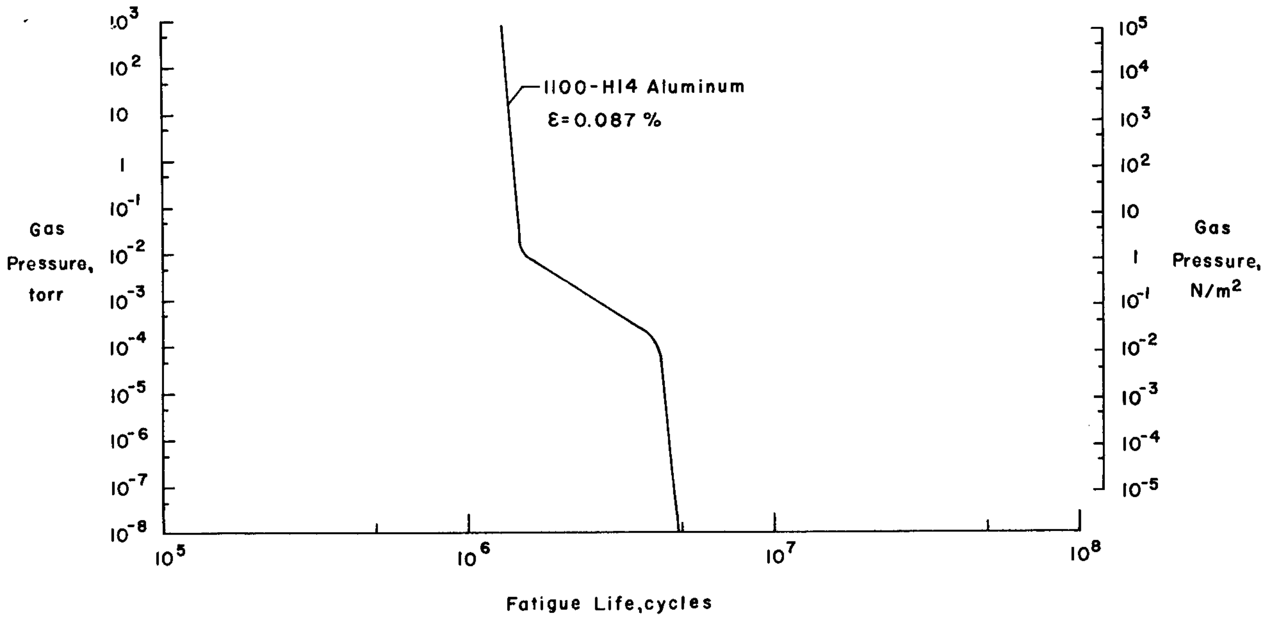


Figure 2.- Stepped variation between fatigue life and gas pressure (from ref. 9). R = -1.

A mechanism based upon a combination of cold-welding and adsorption behavior was proposed to explain the observed variation of life with gas pressure. In the initial stage of fatigue damage accumulation (prior to crack initiation), localized plastic deformation occurs in some surface crystals as a result of fatigue loading. It was assumed that some of this deformation occurs in the form of reversible slip, which initially exposes clean surface material to the gas molecules of the surrounding environment. The buildup of aluminum oxide on this clean surface is time dependent but tends toward an equilibrium thickness at a given pressure; at a higher pressure, the thickness is greater. At higher pressures a sufficient oxide thickness forms the structure characteristic of Al_2O_3. It was proposed that only this structure can be bound tightly enough to the parent material to be carried into the metal when reverse slip occurs. Rebonding of the surfaces is thus inhibited and a crack nucleated. If there is an insufficient thickness of oxide to form Al_2O_3, the attached oxygen can be displaced upon reversal of slip, and the rebonding of the surfaces can be accomplished. It was proposed, therefore, that above 10^{-2} torr (1.33 N/m^2), there is always a sufficient thickness of oxide to form Al_2O_3 and, consequently, fatigue life is governed by the nucleation of oxide-caused cracks. Below 10^{-4} torr (1.33 cN/m^2), there is an insufficient thickness of attached oxygen to form Al_2O_3, and fatigue life is assumed to be influenced by some other damage phenomenon. Between 10^{-2} and 10^{-4} torr (1.33 N/m^2 and 1.33 cN/m^2), there is a transition range, and life varies rapidly within this range.

A stepped variation between the fatigue life and pressure also occurred for pure lead (ref. 6). The rapidly changing portion of the curve for this material occurred between 1.5×10^{-1} and 5×10^{-3} torr (19.9 N/m^2 and 6.67 dN/m^2).

Accompanying this rapidly changing portion of the curve was a transition in the mode of failure from intercrystalline cracking at high gas pressures to extensive slip deformation at lower gas pressures. This transition was attributed to different rates of reaction between the gas and metal at different pressures, which is similar to the process proposed to explain the stepped variation found in aluminum. However, no specific mechanism explaining the stepped variation was proposed.

In yet another investigation (ref. 10), it was found that the life of commercially pure aluminum increased steadily with decreasing pressure from 760 to 2.5×10^{-5} torr (101.3 kN/m^2 to 3.33 mN/m^2), and subsequently decreased from 2.5×10^{-5} to 2×10^{-8} torr (3.33 mN/m^2 to 2.67 $\mu N/m^2$), the limit of the vacuum system. However, the life at 2×10^{-8} torr (2.67 $\mu N/m^2$) was still longer than the life at atmospheric pressure.

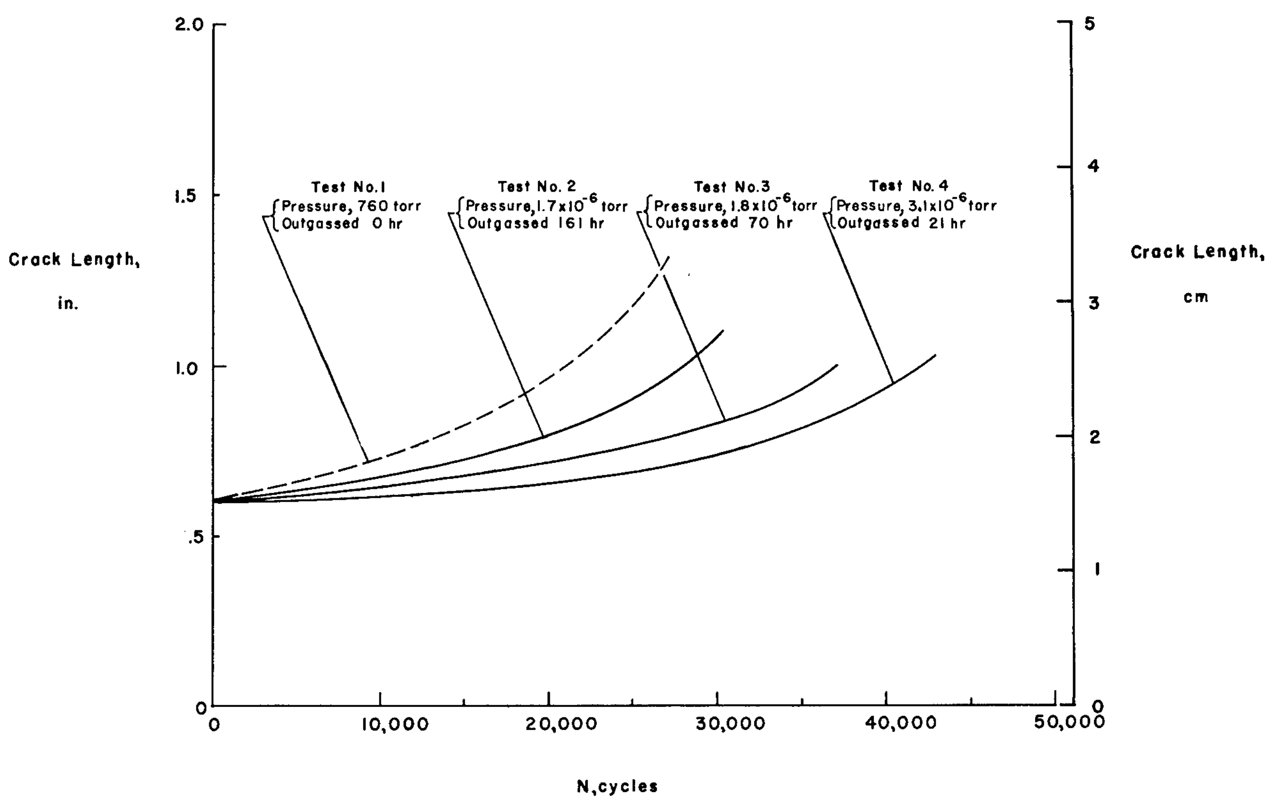
At elevated temperature, 1500° F (1089° K), the curves of fatigue life against pressure for pure nickel and 316 stainless steel exhibited a stepped variation (ref. 11). However, the variation of these curves was almost exactly opposite of the stepped variations in the curves for lead and aluminum. Life increased rapidly with decreasing pressure from 760 to 10^{-3} torr (101.3 kN/m^2 to 1.33 dN/m^2), was constant from about 10^{-3} to 10^{-5} torr (1.33 dN/m^2 to 1.33 mN/m^2), and then increased further with decreasing pressure. No mechanism was proposed to explain this variation.

Effect of Prolonged Exposure to Vacuum on Fatigue Life

To date, little research has been directed toward studying the effects of prolonged exposure to vacuum on the fatigue characteristics of metals. In one investigation (ref. 8), specimens were outgassed (exposed to a vacuum environment to remove adsorbed gases) and, in some instances, baked at 210° F (372° K) for different periods of time before testing in vacuum. The baking was expected to accelerate the removal of the surface layer of adsorbed gases. Axial-load tests were conducted at stress ratios (ratio of the minimum stress to the maximum stress) of 0.5 and -0.5 on centrally notched sheet specimens made of 2014-T6 aluminum alloy. It was found in previous investigations that little scatter occurred in tests of this type which were conducted in the atmosphere. Consequently, little scatter was expected in the tests conducted in vacuum. Any differences in the results were attributed to the differences in the exposure times.

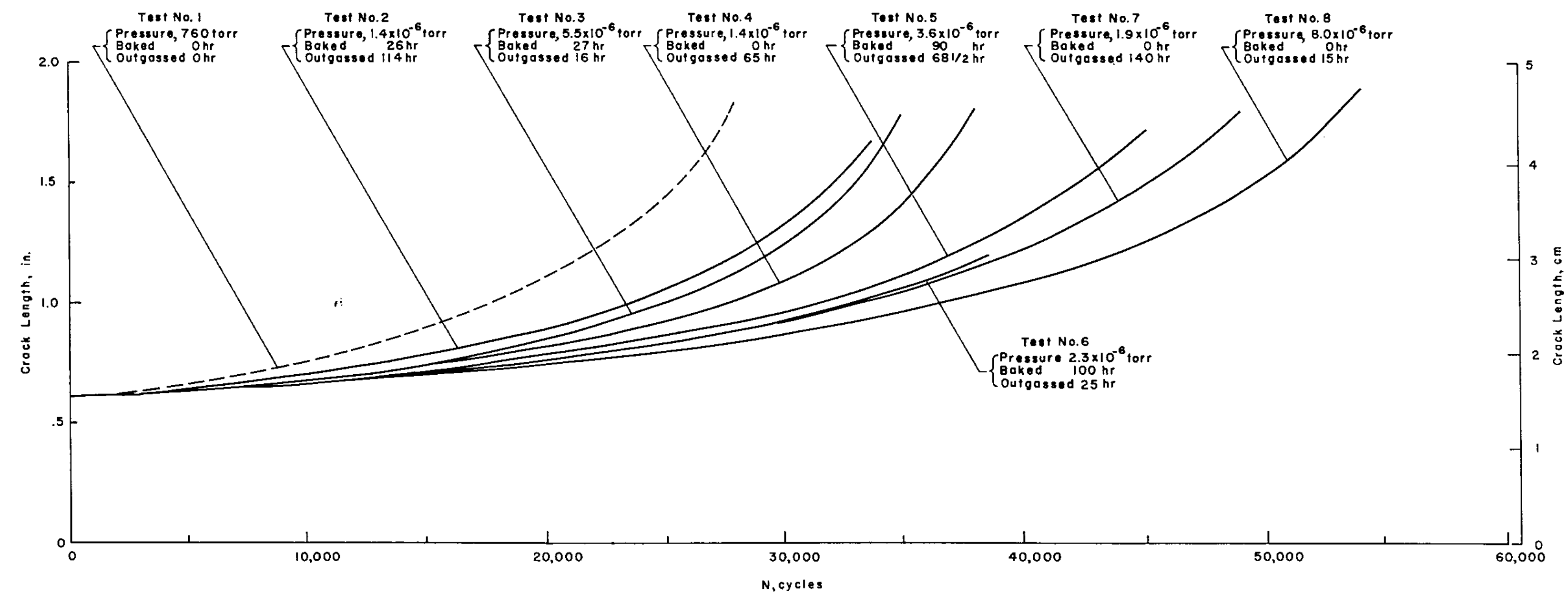
The experimental results are shown in the form of crack length plotted against cycles in figures 3(a) and 3(b). These curves are plotted from the beginning of the fatigue test and, consequently, include both the crack initiation and propagation stages of fatigue. The data in figure 3(a) and some of the data in figure 3(b) indicate that the longer the exposure time the smaller the increase in life in vacuum. In figure 3(b) the lives of specimens tested at a nominal pressure of 2×10^{-6} torr (266.7 $\mu N/m^2$), tests 2, and 4 to 7, are obviously shorter than the lives of specimens tested at 8×10^{-6} torr (1.07 mN/m^2), test 8. This finding is in direct contradiction with the results of short-time

exposure tests which showed that the fatigue life of this material increased continuously with decreasing pressure. Since there are no other obvious variables in the test procedures, the shorter lives at lower pressures are attributable to the prolonged exposure and heating (in vacuum) to which the specimens were subjected before testing. However, if only the data obtained at a nominal pressure of 2×10^{-6} torr (266.7 $\mu N/m^2$) are considered, no consistent trend can be found in the variation of life with exposure. In one instance three specimens having long exposure times, tests 5, 6, and 7, have longer lives than a specimen having less exposure time, test 4. On the other hand, another specimen having a long exposure time, test 2, had a shorter life than the specimen having less exposure time, test 4. No explanation for this behavior is immediately apparent. It may be that the experimental results for this type of test are not as readily reproducible as was believed and that the differences in the curves are merely scatter. Perhaps there is some other explanation. Regardless of the reason, it is clear that these experimental results must be handled cautiously in any attempt to determine the effect of prolonged exposure on fatigue life.



(a) S = 16,000 psi (110.3 MN/m^2); R = 0.5.

Figure 3.- Effect of prolonged exposure to vacuum on the fatigue life of 2014-T6 aluminum alloy (from ref. 8). Test numbers shown were selected for convenience by the present author.



(b) S = 11,000 psi (75.8 MN/m^2); R = -0.5; baked at 210° F (372° K).

Figure 3.- Concluded.

Unpublished data from an investigation made at Battelle Memorial Institute, Columbus, Ohio, indicate that the fatigue lives of 2024-T351 and 7075-T6 aluminum alloys increased with prolonged exposure. Figures 4 and 5 are plots of fatigue life against hours of outgassing before testing. These data are, of course, in direct opposition to the trend found in reference 8. No explanation for these contradictory findings is apparent at this time. Thus, it is obvious that insufficient information is currently available to satisfactorily determine the effects of prolonged exposure on fatigue life.

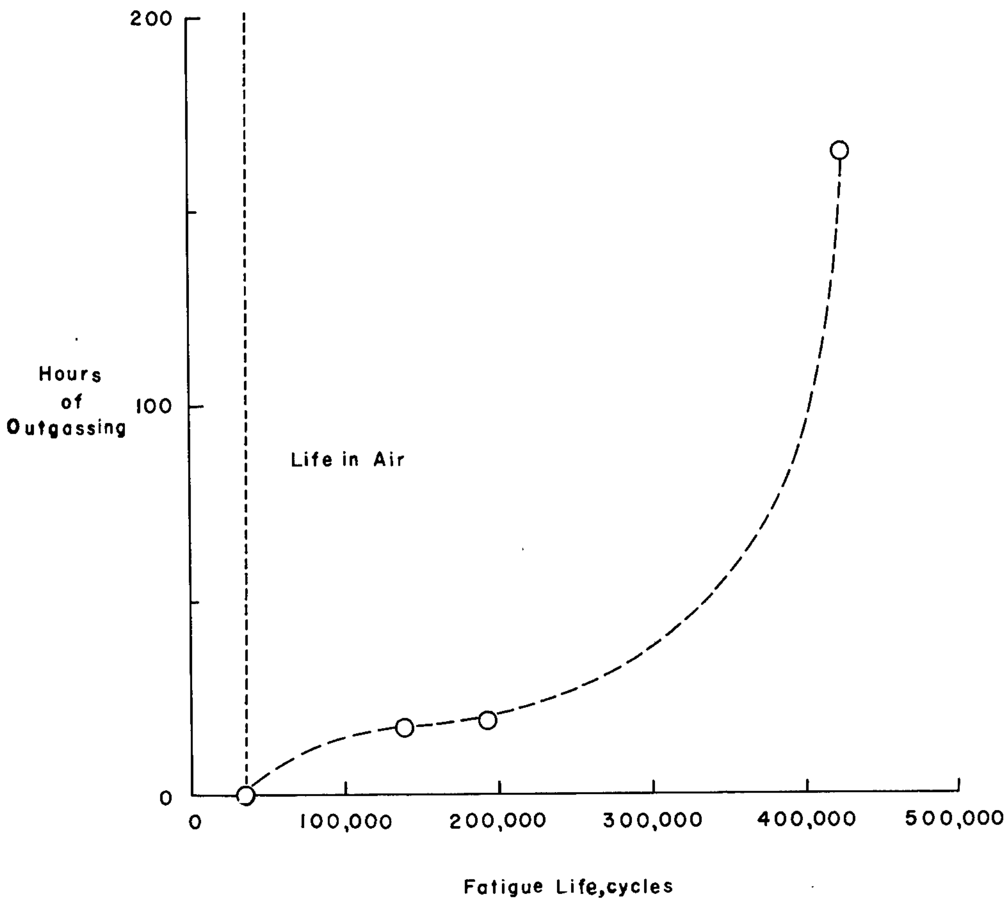


Figure 4.- Effect of prolonged exposure to vacuum on the fatigue life of 2024-T351 aluminum alloy. S = 55,000 psi (379.2 MN/m^2); R = 0; gas pressure nominally 2×10^{-6} torr (266.7 μN/m^2); data obtained from study at Battelle Memorial Institute, Columbus, Ohio.

Long time exposure to vacuum may also result in evaporation of some high-volatility constitutents used to strengthen alloy materials. These evaporation losses could result in a severe reduction in the fatigue strength of these materials. Consequently, study of this possible phenomenon should be given serious consideration in future vacuum fatigue research.

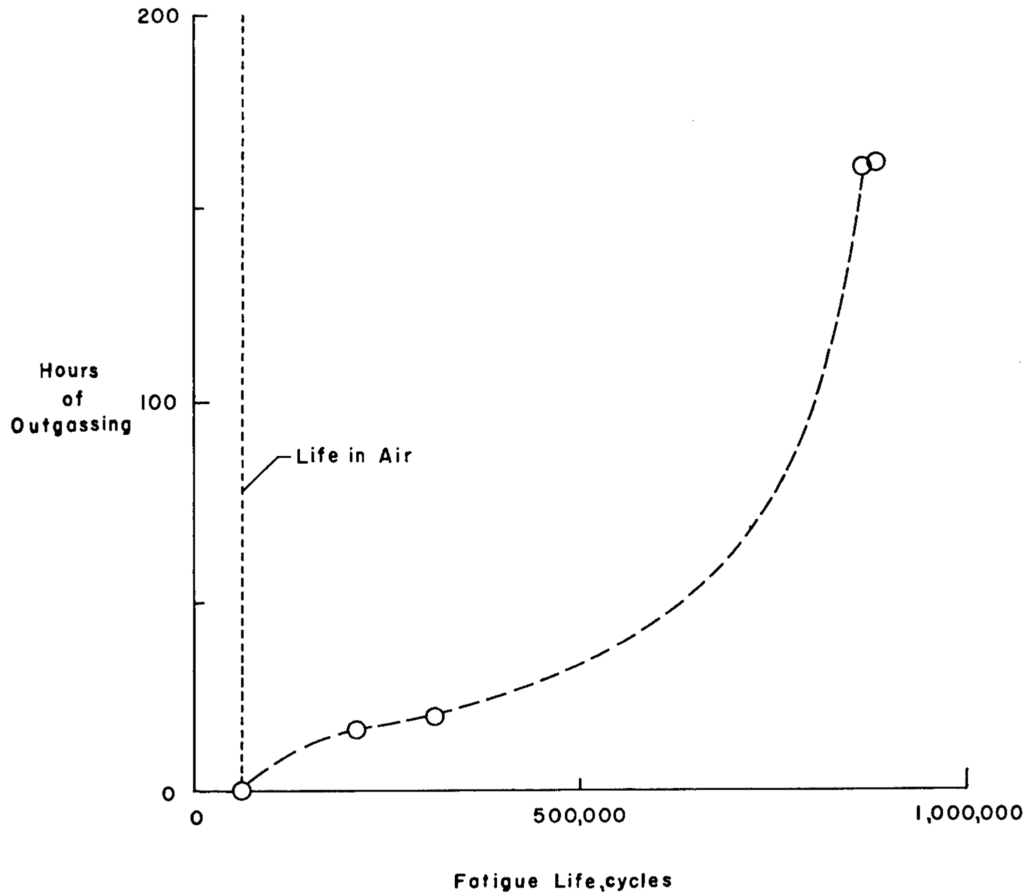


Figure 5.- Effect of prolonged exposure to vacuum on the fatigue life of 7075-T6 aluminum alloy. S = 44,500 psi (306.8 MN/m^2); R = 0; gas pressure nominally 1×10^{-5} torr (1.33 mN/m^2); data obtained from study at Battelle Memorial Institute, Columbus, Ohio.

Vacuum Fatigue at Elevated Temperature

Constant-amplitude bending fatigue tests were conducted on specimens of 316 stainless steel, pure nickel, and an age-hardenable nickel-chromium alloy (described in ref. 12) in the atmosphere and at pressures of 1×10^{-5}, 5×10^{-6}, and 2×10^{-6} torr (1.33 mN/m^2, 666.7 μN/m^2), and 266.7 μN/m^2), respectively. (See refs. 13 to 16.) All tests in both air and vacuum were conducted at a temperature of 1500° F (1089° K). Experimental results show that the fatigue lives of all these materials were longer in vacuum than in air at high strain levels. However, at lower strain levels (albeit plastic in some instances) the fatigue life in air approached and, in some cases, exceeded the fatigue life in vacuum. An example of this behavior in pure nickel is shown in figure 6 (from ref. 13). In figure 6, the number of cycles to failure is plotted against the total plastic strain per half cycle in accordance with the procedure of reference 17. (Tavernelli and Coffin (ref. 17) have proposed that for fatigue

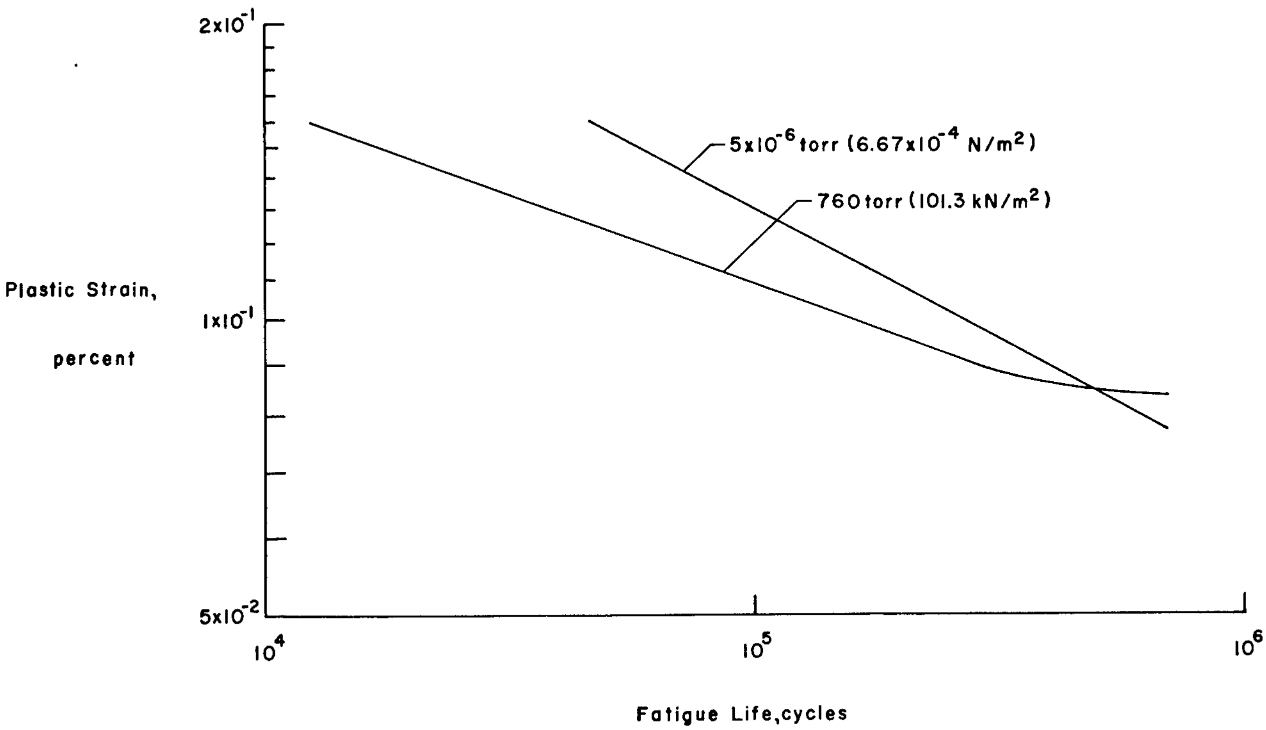


Figure 6.- Fatigue-life curves for pure nickel (from ref. 13). R = -1; temperature of 1500° F (1089° K).

tests in which the yield strength of the material is exceeded, only the plastic strain portion of the loading cycle is significant.)

It was proposed that the fatigue life was longer in vacuum than in air at high strain levels because the oxygen in the air reacts with the atoms at the crack tip and reduces the work necessary to break the interatomic bonds. In vacuum there is less available oxygen; consequently, less reduction in the interatomic bonding occurs and fatigue life is longer. This mechanism corresponds closely to one proposed in references 3 and 4.

A concomitant mechanism was offered to explain the trend toward longer fatigue lives in air than in vacuum at lower strain levels. It was proposed that at the lower strain levels, fatigue cracks exposed to the air fill with oxides which become tensile-load bearing. These load-bearing oxides relieve some of the stress at the crack tip and consequently increase fatigue life.

In vacuum there is less available oxygen to form these load-bearing oxides, and consequently, the fatigue life is shorter. This latter mechanism is described as a time-dependent process, which only becomes dominant at the lower stress levels where the fatigue life is longer and there is more time for these load-bearing oxides to form.

Effect of Vacuum on Surface Deformation

Study of specimen surfaces by a number of researchers (refs. 3, 4, 6, 7, 9, and 18) revealed that specimen surfaces which were initially smooth become visibly roughened after testing in vacuum, whereas the surfaces of specimens tested in air generally remain smooth. In addition, specimens tested in vacuum generally contained a larger number of cracks than similar specimens tested in air. Figure 7 illustrates the advanced degree of surface cracking which occurs in specimens investigated in vacuum.

The increased number of cracks is generally attributed to a decreased rate of crack growth in vacuum. In some instances, cracks were found to stop growing altogether. This retardation in the growth of the initial crack provides time for additional cracks to form and propagate. Intermittent coldwelding of the fractured surface on the compression portion of the loading cycle is generally believed to be the cause of this retarded crack growth.

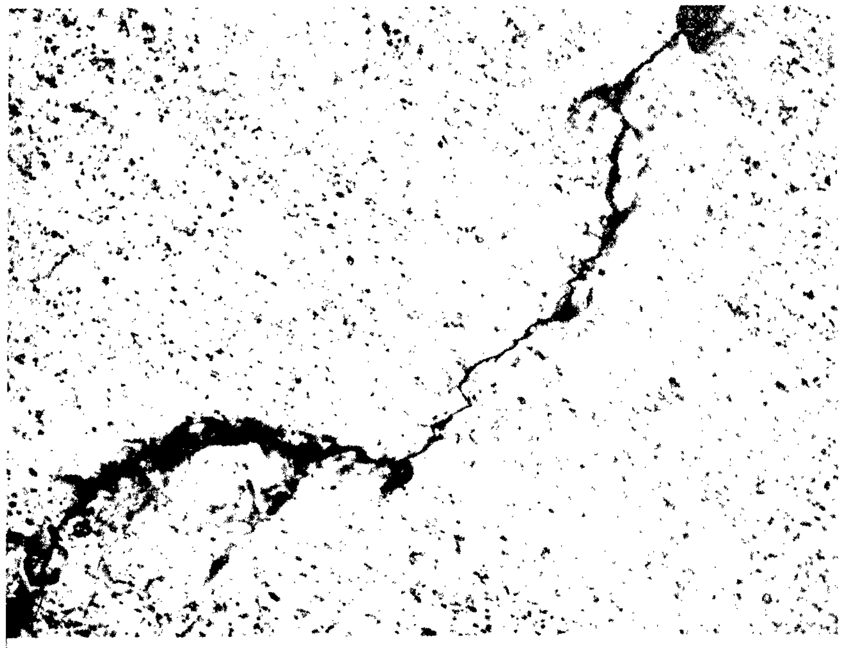
The increased surface roughening occurring in vacuum is usually attributed to increased slip. No mechanism explaining this increased roughening was found in this survey of the literature.

In one instance (ref. 2), superficial inspection of specimens revealed no differences between the surfaces of specimens tested in air and those tested in vacuum. However, in the vacuum tests the gas pressures were several orders of magnitude higher than the lowest pressures used in the other investigations, and this might account for the negligible surface deformation reported.

Effect of Composition of Environment on Fatigue Life

One of the greatest contributions of research in vacuum fatigue may be the identification of constitutents in the atmosphere which have a detrimental effect upon fatigue life. A limited amount of experimental evidence already indicates that it is the absence of deleterious constitutents rather than low gas pressure which is responsible for the increased fatigue life found in vacuum. Water vapor was found to be a dominant factor governing the fatigue life of aluminum in three separate investigations (refs. 4, 9, and 19). The combined results indicated that at a given gas pressure, be it atmospheric or in the vacuum range, the fatigue life of aluminum is significantly greater in an environment having a low water vapor content than in one having a high water vapor content. These results are in general agreement with the results of tests conducted by other investigators at atmospheric pressure only.

In order to determine which constitutent of the water vapor was the most deleterious to fatigue life, tests were conducted on aluminum specimens at atmospheric pressure in environments of gaseous oxygen, nitrogen, and hydrogen (ref. 19). The results showed that the life in gaseous oxygen and nitrogen was much greater than the life in gaseous hydrogen. Thus, it was proposed that the hydrogen was the most damaging constitutent, and the changes in life were attributed to the diffusion of hydrogen ions into the material rather than the adsorption of oxygen onto the surface.



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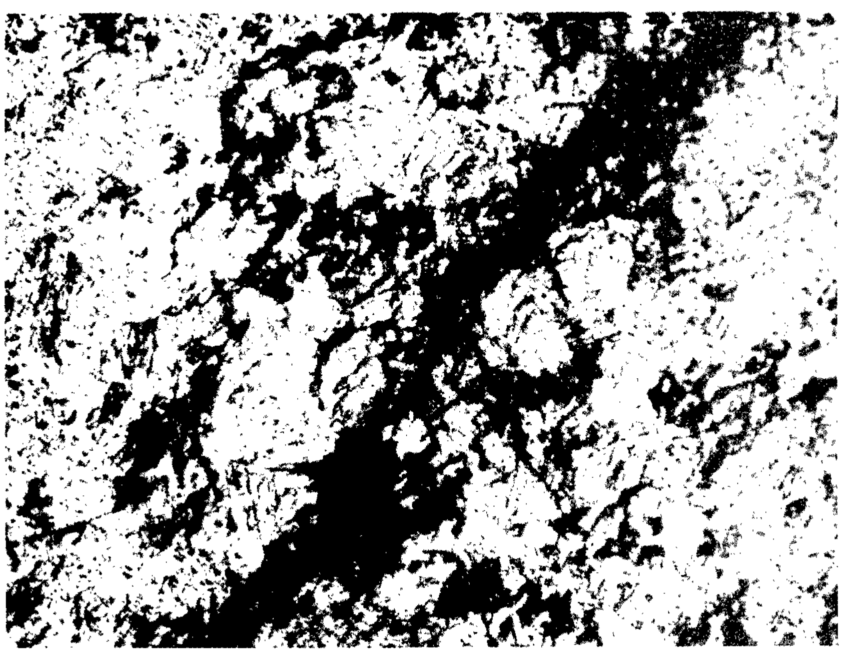
(a) Investigated in air. Nominal ϵ, 0.087 percent; cycles to failure, 6.78×10^5.



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(b) Investigated in vacuum. Nominal ϵ, 0.081 percent; cycles to failure, 3.88×10^6.

Figure 7.- Surfaces of fatigued aluminum specimens (from ref. 9).

Three possible mechanisms were proposed. In the first mechanism, the hydrogen ions diffuse into the metal and accumulate at voids which exist in the metal. The constant diffusion of these ions builds up internal pressure in the voids which facilitates crack initiation. In the second mechanism, the diffusion of hydrogen ions alters the surface energy of cracks and, thus, modifies the rate at which they grow. In the third suggested mechanism, the rate of diffusion of the hydrogen ions governs the generation of voids by controlling the clustering of vacancies formed by moving dislocations.

A combination of gaseous oxygen and water vapor was found to cause a major reduction in the fatigue life of copper in references 3 and 20. In both investigations, it was reported that water vapor alone had no effect upon fatigue life, which is exactly the opposite effect found for aluminum. No explanation is offered for this contradictory finding (refs. 4, 9, and 19).

In one of the investigations of copper (ref. 3), it was reported that gaseous oxygen alone significantly reduced the fatigue life, although a combination of oxygen and water vapor had more effect. In the other investigation (ref. 20), it was reported that gaseous oxygen was not particularly effective in reducing fatigue life by itself. Again, there was no explanation of these conflicting findings.

DISCUSSION

Most of the experimental results reported to date indicate that fatigue life was improved as a result of testing in vacuum. The mechanisms proposed by the various investigators to explain this improvement can be classified into two general categories: one involves the cold-welding process, whereas the other involves a decrease in deleterious interaction between the material and the vacuum environment.

It has been shown that the conditions necessary for cold-welding can be satisfied in a vacuum fatigue test. Consequently, this mechanism must be given serious consideration as the possible cause of improved fatigue life in vacuum. A series of vacuum fatigue tests conducted at some positive stress ratios such that the newly cracked surfaces are never brought back into contact could provide an expedient way of establishing the validity of this cold-welding mechanism.

The decreased interaction mechanism also merits consideration as a possible explanation of the increased fatigue life found in vacuum. The results of tests on aluminum and copper (refs. 3, 4, 9, 19, and 20) showed rather convincingly that water vapor and/or oxygen had a detrimental effect upon fatigue life. Additional support for this interaction mechanism may be derived from the following reasoning. Fatigue is generally thought to be a mechanical process which begins with the movement of surface dislocations actuated by cyclic loadings. These dislocation movements form slip steps on the surface of specimens which ultimately develop into fatigue cracks. The cracks propagate until the remaining material can no longer carry the cyclic loading and the part fails statically. In vacuum fatigue the development of slip steps appears to

be accelerated, as evidenced by the increased surface roughening. From the preceding process, it would be expected that accelerated slip step formation would result in a decrease in the fatigue life, and yet, the fatigue life is found to increase in vacuum. Clearly, there must be some additional factor operating which has been omitted from the preceding process, and this factor quite possibly involves some interaction between the environment and the material which is deleterious to fatigue life.

If this interaction mechanism is valid, then additional research could lead to definite identification of the damaging constitutents in the atmosphere. It might then be possible to develop alloys which are highly resistant to these constitutents and, consequently, have improved fatigue lives.

The exterior surface roughening found in the vacuum fatigue tests could also become a significant consideration in the design of future spacecraft. If the material subjected to alternating loadings should be an optical or bearing surface, malfunction of the part could result from the roughening. In addition, if the surface were painted for heat control, the paint could be knocked off, and thus, the thermodynamic properties of the surface would be changed.

The need for additional research into the effects of prolonged exposure is obvious. If life is dependent upon the time over which the material is exposed to vacuum, then this dependence should be established and taken into account in the design of future space vehicles. Similarly, the effects of temperature upon vacuum fatigue characteristics should be studied in greater detail.

An investigation directed toward determining the effects of a vacuum environment upon engineering materials should be conducted since most of the materials tested to date have been of academic interest only. In addition, tests should be conducted on specimens containing notches. Space vehicles will contain numerous stress concentrations, that is, rivet holes, fillets, welds, and so forth. Consequently, specimens containing stress concentrations of equivalent severity should be tested to obtain a representative prediction of the behavior of the material in a space environment.

Finally, the possible effects of radiation on the vacuum fatigue phenomenon should be studied. As previously stated, fatigue is usually considered to be a surface phenomenon, and radiation may effect changes in the surfaces of metals which can modify vacuum fatigue behavior.

CONCLUDING REMARKS

The literature has been surveyed for reports on the subject of fatigue in vacuum, and the following observations have been made on the findings reported therein:

(1) Fatigue life is increased as a result of testing in vacuum, although the manner in which life varies with decreasing pressure (e.g., continuous or stepwise) has not been established as yet.

(2) Water vapor in a gaseous environment was generally found to be quite deleterious to fatigue life.

(3) The results of the few tests conducted after prolonged exposure to vacuum are contradictory. In one instance, it appears that the increase in life in vacuum is not as great after prolonged exposure; in another instance, life increased with increasing exposure time.

(4) Considerably more slip occurred on the exterior surfaces of specimens tested in vacuum than on the surfaces of specimens tested in air.

(5) A number of mechanisms were proposed to explain the findings described. To date, however, none of these mechanisms has been verified. The mechanisms are proposed simply to explain the phenomenon found in experimental studies.

In order to provide information useful for the design of future space vehicles, additional vacuum fatigue research should be concentrated on the engineering materials rather than the academic materials primarily used to date. The specimen configurations for this research should include stress concentrations to simulate structural stress distribution, and the tests should be conducted at a number of stress ratios in order to evaluate material performance over a wide range of practical stress conditions. Tests at positive stress ratios, where the newly cracked surfaces are not brought back into contact, might be used to evaluate the cold-welding mechanism proposed to explain increased fatigue life in vacuum.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 6, 1964.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units, abbreviated SI (Systeme International), was adopted in 1960 by the Eleventh General Conference on Weights and Measures held in Paris, France. (See ref. 1.) Conversion factors required for units used herein are given in the following table:

Physical quantity	U.S. customary unit	Conversion factor (*)	SI unit
Length	in.	2.54×10^{-2}	meters (m)
Stress	psi	6.894757×10^{3}	newton/meter^2 (N/m^2)
Pressure	torr	133.322	newton/meter^2 (N/m^2)
Temperature	$^{\circ}$F	$\frac{5}{9}(^{\circ}F + 459.67)$	degrees Kelvin ($^{\circ}$K)

*Multiply value given in U.S. customary unit by conversion factor to obtain equivalent value in SI unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
deci (d)	10^{-1}
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}
kilo (k)	10^{3}
mega (M)	10^{6}

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TABLE I.- SUMMARY OF THE EFFECTS OF VACUUM ON FATIGUE

(a) U.S. customary units

Ref.	Material	Loading	Pressure range, torr	Other variable	Maximum stress or strain	Effect of vacuum on fatigue
3	OFHC copper	Completely reversed bending	760 to 10^{-5}		$\epsilon = 0.127\%$	$N_{-1}/N_3 \approx 4$; $N_{-3}/N_3 \approx 10$; $N_{-5}/N_3 \approx 20$
3	OFHC copper	Completely reversed bending	760 to 10^{-5}	Environment of wet oxygen at 760 torr	$\epsilon = 0.127\%$	$N_{-1}/N_3 \approx 8$; $N_{-3}/N_3 \approx 20$; $N_{-5}/N_3 \approx 40$
3	Pure aluminum	Completely reversed bending	760 to 10^{-5}		$\epsilon = 0.088\%$	$N_{-1}/N_3 \approx 1.6$; $N_{-3}/N_3 \approx 3$; $N_{-5}/N_3 \approx 5$
3	Pure aluminum	Completely reversed bending	760 to 10^{-5}	Water vapor at 10 torr	$\epsilon = 0.088\%$	$N_{-1}/N_1 \approx 3$; $N_{-3}/N_1 \approx 4$; $N_{-5}/N_1 \approx 8$
3	High-purity Al-5.6%Zn-2.7%Mg-0.5%Cu alloy	Completely reversed bending	760 to 10^{-5}		$\epsilon = 0.246\%$	$N_{-1}/N_3 \approx 4$; $N_{-3}/N_3 \approx 8$; $N_{-5}/N_3 \approx 16$
6	High-purity rolled lead strip	Completely reversed bending	760 to 10^{-6}		$\epsilon = 0.140\%$	$N_0/N_3 \approx 1$; $N_{-3}/N_3 \approx 8$; $N_{-6}/N_3 \approx 8$
6	High-purity rolled lead strip	Completely reversed bending	760 to 10^{-6}		$\epsilon = 0.092\%$	$N_0/N_3 \approx 1$; $N_{-3}/N_3 \approx 25$; $N_{-6}/N_3 \approx 25$
6	High-purity rolled lead strip	Completely reversed bending	760 to 10^{-6}		$\epsilon = 0.075\%$	$N_0/N_3 \approx 1$; $N_{-3}/N_3 \approx 62$; $N_{-6}/N_3 \approx 62$
6	Pure aluminum	Completely reversed bending	760 to 10^{-6}		$\epsilon = 0.140\%$	$N_0/N_3 \approx 1.1$; $N_{-3}/N_3 \approx 1.7$; $N_{-6}/N_3 \approx 2.5$
6	Pure aluminum	Completely reversed bending	760 to 10^{-6}		$\epsilon = 0.092\%$	$N_0/N_3 \approx 1.3$; $N_{-3}/N_3 \approx 3.0$; $N_{-6}/N_3 \approx 5.4$
7	Pure-aluminum crystals	Completely reversed bending	760 to 10^{-8}		$\epsilon = 0.069\%$	$N_{-1}/N_3 \approx 4$; $N_{-5}/N_3 \approx 16$; $N_{-8}/N_3 \approx 40$
8	2014-T6 aluminum alloy Al	Axial, R = -0.5	760 and 10^{-5}	15 hours outgassing at 10^{-5} torr before testing	S = 11,000 psi	$N_{-5}/N_3 \approx 1.9$
8	2014-T6 aluminum alloy	Axial, R = -0.5	760 and 10^{-6}	140 hours outgassing at 10^{-6} torr before testing	S = 11,000 psi	$N_{-6}/N_3 \approx 1.7$
8	2014-T6 aluminum alloy	Axial, R = -0.5	760 and 10^{-6}	25 hours outgassing at 10^{-6} torr, and 100 hours baking at 210° F before testing	S = 11,000 psi	$N_{-6}/N_3 \approx 1.8$
8	2014-T6 aluminum alloy	Axial, R = -0.5	760 and 10^{-6}	68.5 hours outgassing at 10^{-6} torr, and 90 hours baking at 210° F before testing	S = 11,000 psi	$N_{-6}/N_3 \approx 1.7$
8	2014-T6 aluminum alloy	Axial, R = -0.5	760 and 10^{-6}	65 hours outgassing at 10^{-6} torr before testing	S = 11,000 psi	$N_{-6}/N_3 \approx 1.3$
8	2014-T6 aluminum alloy	Axial, R = -0.5	760 and 10^{-6}	114 hours outgassing at 10^{-6} torr, and 26 hours baking at 210° F before testing	S = 11,000 psi	$N_{-6}/N_3 \approx 1.2$
8	2014-T6 aluminum alloy	Axial, R = 0.5	760 and 10^{-6}	21 hours outgassing at 10^{-6} torr before testing	S = 16,000 psi	$N_{-6}/N_3 \approx 2.1$
8	2014-T6 aluminum alloy	Axial, R = 0.5	760 and 10^{-6}	70 hours outgassing at 10^{-6} torr before testing	S = 16,000 psi	$N_{-6}/N_3 \approx 1.8$
8	2014-T6 aluminum alloy	Axial, R = 0.5	760 and 10^{-6}	161 hours outgassing at 10^{-6} torr before testing	S = 16,000 psi	$N_{-6}/N_3 \approx 1.4$
9	1100-H14 rolled aluminum strip Al	Completely reversed bending	760 to 10^{-8}	Dry air at all pressures	$\epsilon = 0.087\%$	$N_{-2}/N_3 \approx 1.2$; $N_{-4}/N_3 \approx 4$; $N_{-8}/N_3 \approx 4$
9	1100-H14 rolled aluminum strip	Completely reversed bending	760 to 10^{-8}		$\epsilon = 0.087\%$	$N_{-2}/N_3 \approx 2.1$; $N_{-4}/N_3 \approx 7$; $N_{-8}/N_3 \approx 7$

TABLE I.- SUMMARY OF THE EFFECTS OF VACUUM ON FATIGUE - Continued

(a) U.S. customary units - Concluded

Ref.	Material	Loading	Pressure range, torr	Other variable	Maximum stress or strain	Effect of vacuum on fatigue
10	1100-H16 aluminum	Completely reversed bending	760 to 10^{-8}		S = 11,300 psi	$N_{-5}/N_3 \approx 8$; $N_{-6}/N_3 \approx 5$; $N_{-8}/N_3 \approx 3$
11	316 stainless steel SS	Completely reversed bending	760 to 10^{-6}	Tests at 1500° F	$\epsilon_p = 0.146\%$	$N_{-1}/N_3 \approx 7$; $N_{-4}/N_3 \approx 11$; $N_{-6}/N_3 \approx 21$
11	Pure nickel	Completely reversed bending	760 to 10^{-6}	Tests at 1500° F	$\epsilon_p = 0.146\%$	$N_{-3}/N_3 \approx 6$; $N_{-5}/N_3 \approx 6$; $N_{-6}/N_3 \approx 10$
(a)	2024-T351 aluminum alloy Al	Axial, $R \approx 0$	760 and 10^{-6}	17 hours outgassing at 10^{-6} torr before testing	S = 55,000 psi	$N_{-6}/N_3 \approx 4.5$
(a)	2024-T351 aluminum alloy	Axial, $R \approx 0$	760 and 3×10^{-6}	19 hours outgassing at 3×10^{-6} torr before testing	S = 55,000 psi	$N_{-6}/N_3 \approx 6.2$
(a)	2024-T351 aluminum alloy	Axial, $R \approx 0$	760 and 3×10^{-6}	164 hours outgassing at 3×10^{-6} torr before testing	S = 55,000 psi	$N_{-6}/N_3 \approx 13.7$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	760 and 10^{-5}	16 hours outgassing at 10^{-5} torr before testing	S = 44,500 psi	$N_{-5}/N_3 \approx 3.3$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	760 and 10^{-5}	19 hours outgassing at 10^{-5} torr before testing	S = 44,500 psi	$N_{-5}/N_3 \approx 4.9$
(a)	7075-T6 aluminum alloy Al	Axial, $R \approx 0$	760 and 10^{-5}	160 hours outgassing at 10^{-5} torr before testing	S = 44,500 psi	$N_{-5}/N_3 \approx 13.7$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	760 and 10^{-5}	161 hours outgassing at 7×10^{-6} torr before testing	S = 44,500 psi	$N_{-5}/N_3 \approx 13.6$
13	Pure nickel	Completely reversed bending	760 and 10^{-6}	Tests at 1500° F	$\epsilon_p = 1.6\%$	$N_{-6}/N_3 \approx 5$
13	Pure nickel	Completely reversed bending	760 and 10^{-6}	Tests at 1500° F	$\epsilon_p = 0.6\%$	$N_{-6}/N_3 \approx 0.3$
13	Age-hardenable nickel-chromium alloy	Completely reversed bending	760 and 10^{-6}	Tests at 1500° F	$\epsilon = 1.7\%$	$N_{-6}/N_3 \approx 15$
13	Age-hardenable nickel-chromium alloy	Completely reversed bending	760 and 10^{-6}	Tests at 1500° F	$\epsilon = 1.3\%$	$N_{-6}/N_3 \approx 4$
13	316 stainless steel	Completely reversed bending	760 and 10^{-5}	Tests at 1500° F	$\epsilon = 2.2\%$	$N_{-5}/N_3 \approx 21$
13	316 stainless steel	Completely reversed bending	760 and 10^{-5}	Tests at 1500° F	$\epsilon = 1.0\%$	$N_{-5}/N_3 \approx 4$
18	High-purity rolled lead strip	Completely reversed bending	760 and 5×10^{-3}		$\epsilon = 0.15\%$	$N_{-3}/N_3 \approx 7$
18	High-purity rolled lead strip	Completely reversed bending	760 and 5×10^{-3}		$\epsilon = 0.10\%$	$N_{-3}/N_3 \approx 19$
19	Aluminum - 4% copper alloy	Completely reversed bending	760 and 10^{-6}		S = 26,800 psi	$N_{-6}/N_3 \approx 4$
19	Aluminum - 4% copper alloy	Completely reversed bending	760 and 10^{-6}	Dry air at 10^{-6} torr	S = 26,800 psi	$N_{-6}/N_3 \approx 9$
19	Aluminum - 4% copper alloy	Completely reversed bending	760 and 17.5	Wet air at 17.5 torr	S = 26,800 psi	$N_1/N_3 \approx 0.6$

[a] Data obtained from Battelle Memorial Institute, Columbus, Ohio.

TABLE I.- SUMMARY OF THE EFFECTS OF VACUUM ON FATIGUE - Continued

(b) International system of units

Ref.	Material	Loading	Pressure range, N/m^2	Other variable	Maximum stress, or strain	Effect of vacuum on fatigue
3	OFHC copper	Completely reversed bending	1.01×10^5 to 1.33×10^{-3}		$\epsilon = 0.127\%$	$N_1/N_5 \approx 4$; $N_{-1}/N_5 \approx 10$; $N_{-3}/N_5 \approx 20$
3	OFHC copper	Completely reversed bending	1.01×10^5 to 1.33×10^{-3}	Environment of wet oxygen at 1.01×10^5 N/m^2	$\epsilon = 0.127\%$	$N_1/N_5 \approx 8$; $N_{-1}/N_5 \approx 20$; $N_{-3}/N_5 \approx 40$
3	Pure aluminum	Completely reversed bending	1.01×10^5 to 1.33×10^{-3}		$\epsilon = 0.088\%$	$N_1/N_5 \approx 1.6$; $N_{-1}/N_5 \approx 3$; $N_{-3}/N_5 \approx 5$
3	Pure aluminum	Completely reversed bending	1.01×10^5 to 1.33×10^{-3}	Water vapor at 1.33×10^3 N/m^2	$\epsilon = 0.088\%$	$N_1/N_3 \approx 3$; $N_{-1}/N_3 \approx 4$; $N_{-3}/N_3 \approx 8$
3	High-purity Al-5.6%Zn-2.7%Mg-0.5%Cu alloy	Completely reversed bending	1.01×10^5 to 1.33×10^{-3}		$\epsilon = 0.246\%$	$N_1/N_5 \approx 4$; $N_{-1}/N_5 \approx 8$; $N_{-3}/N_5 \approx 16$
6	High-purity rolled lead strip	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}		$\epsilon = 0.140\%$	$N_2/N_5 \approx 1$; $N_{-1}/N_5 \approx 8$; $N_{-4}/N_5 \approx 8$
6	High-purity rolled lead strip	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}		$\epsilon = 0.092\%$	$N_2/N_5 \approx 1$; $N_{-1}/N_5 \approx 25$; $N_{-4}/N_5 \approx 25$
6	High-purity rolled lead strip	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}		$\epsilon = 0.075\%$	$N_2/N_5 \approx 1$; $N_{-1}/N_5 \approx 62$; $N_{-4}/N_5 \approx 62$
6	Pure aluminum	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}		$\epsilon = 0.140\%$	$N_2/N_5 \approx 1.1$; $N_{-1}/N_5 \approx 1.7$; $N_{-4}/N_5 \approx 2.5$
6	Pure aluminum	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}		$\epsilon = 0.092\%$	$N_2/N_5 \approx 1.3$; $N_{-1}/N_5 \approx 3.0$; $N_{-4}/N_5 \approx 5.4$
7	Pure-aluminum crystals	Completely reversed bending	1.01×10^5 to 1.33×10^{-6}		$\epsilon = 0.069\%$	$N_1/N_5 \approx 4$; $N_{-3}/N_5 \approx 16$; $N_{-6}/N_5 \approx 40$
8	2014-T6 aluminum alloy	Axial, R = -0.5	1.01×10^5 to 1.33×10^{-3}	15 hours outgassing at 1.33×10^{-3} N/m^2 before testing	$S = 75.8$ MN/m^2	$N_{-3}/N_5 \approx 1.9$
8	2014-T6 aluminum alloy	Axial, R = -0.5	1.01×10^5 to 1.33×10^{-4}	140 hours outgassing at 1.33×10^{-4} N/m^2 before testing	$S = 75.8$ MN/m^2	$N_{-4}/N_5 \approx 1.7$
8	2014-T6 aluminum alloy	Axial, R = -0.5	1.01×10^5 to 1.33×10^{-4}	25 hours outgassing at 1.33×10^{-4} N/m^2, and 100 hours baking at 372° K before testing	$S = 75.8$ MN/m^2	$N_{-4}/N_5 \approx 1.8$
8	2014-T6 aluminum alloy	Axial, R = -0.5	1.01×10^5 and 1.33×10^{-4}	68.5 hours outgassing at 1.33×10^{-4} N/m^2, and 90 hours baking at 372° K before testing	$S = 75.8$ MN/m^2	$N_{-4}/N_5 \approx 1.7$
8	2014-T6 aluminum alloy	Axial, R = -0.5	1.01×10^5 and 1.33×10^{-4}	65 hours outgassing at 1.33×10^{-4} N/m^2 before testing	$S = 75.8$ MN/m^2	$N_{-4}/N_5 \approx 1.3$
8	2014-T6 aluminum alloy	Axial, R = -0.5	1.01×10^5 and 1.33×10^{-4}	114 hours outgassing at 1.33×10^{-4} N/m^2, and 26 hours baking at 372° K before testing	$S = 75.8$ MN/m^2	$N_{-4}/N_5 \approx 1.2$
8	2014-T6 aluminum alloy	Axial, R = 0.5	1.01×10^5 and 1.33×10^{-4}	21 hours outgassing at 1.33×10^{-4} N/m^2 before testing	$S = 110.3$ MN/m^2	$N_{-4}/N_5 \approx 2.1$
8	2014-T6 aluminum alloy	Axial, R = 0.5	1.01×10^5 and 1.33×10^{-4}	70 hours outgassing at 1.33×10^{-4} N/m^2 before testing	$S = 110.3$ MN/m^2	$N_{-4}/N_5 \approx 1.8$

TABLE I.- SUMMARY OF THE EFFECTS OF VACUUM ON FATIGUE - Concluded

(b) International system of units - Concluded

Ref.	Material	Loading	Pressure range, N/m^2	Other variable	Maximum stress, or strain	Effect of vacuum on fatigue
8	2014-T6 aluminum alloy	Axial, $R = 0.5$	1.01×10^5 and 1.33×10^{-4}	161 hours outgassing at 1.33×10^{-4} N/m^2 before testing	$S = 110.3$ MN/m^2	$N_{-4}/N_5 \approx 1.4$
9	1100-H14 rolled aluminum strip	Completely reversed bending	1.01×10^5 to 1.33×10^{-6}	Dry air at all pressures	$\epsilon = 0.087\%$	$N_0/N_5 \approx 1.2$; $N_{-2}/N_5 \approx 4$; $N_{-6}/N_5 \approx 4$
9	1100-H14 rolled aluminum strip	Completely reversed bending	1.01×10^5 to 1.33×10^{-6}		$\epsilon = 0.087\%$	$N_0/N_5 \approx 2.1$; $N_{-2}/N_5 \approx 7$; $N_{-6}/N_3 \approx 7$
10	1100-H16 aluminum	Completely reversed bending	1.01×10^5 to 1.33×10^{-6}		$S = 77.9$ MN/m^2	$N_{-3}/N_5 \approx 8$; $N_{-4}/N_5 \approx 5$; $N_{-6}/N_5 \approx 3$
11	316 stainless steel	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}	Tests at 1089° K	$\epsilon_p = 0.146\%$	$N_1/N_5 \approx 7$; $N_{-2}/N_5 \approx 11$; $N_{-4}/N_5 \approx 21$
11	Pure nickel	Completely reversed bending	1.01×10^5 to 1.33×10^{-4}	Tests at 1089° K	$\epsilon_p = 0.146\%$	$N_{-1}/N_5 \approx 6$; $N_{-3}/N_5 \approx 6$; $N_{-4}/N_5 \approx 10$
(a)	2024-T351 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 1.33×10^{-4}	17 hours outgassing at 1.33×10^{-4} N/m^2 before testing	$S = 379.2$ MN/m^2	$N_{-4}/N_5 \approx 4.5$
(a)	2024-T351 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 3.99×10^{-4}	19 hours outgassing at 3.99×10^{-4} N/m^2 before testing	$S = 379.2$ MN/m^2	$N_{-4}/N_5 \approx 6.2$
(a)	2024-T351 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 3.99×10^{-4}	164 hours outgassing at 3.99×10^{-4} N/m^2 before testing	$S = 379.2$ MN/m^2	$N_{-4}/N_5 \approx 13.7$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 1.33×10^{-3}	16 hours outgassing at 1.33×10^{-3} N/m^2 before testing	$S = 306.8$ MN/m^2	$N_{-3}/N_5 \approx 3.3$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 1.33×10^{-3}	19 hours outgassing at 1.33×10^{-3} N/m^2 before testing	$S = 306.8$ MN/m^2	$N_{-3}/N_5 \approx 4.9$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 1.33×10^{-3}	160 hours outgassing at 1.33×10^{-3} N/m^2 before testing	$S = 306.8$ MN/m^2	$N_{-3}/N_5 \approx 13.7$
(a)	7075-T6 aluminum alloy	Axial, $R \approx 0$	1.01×10^5 and 1.33×10^{-3}	161 hours outgassing at 9.33×10^{-4} N/m^2 before testing	$S = 306.8$ MN/m^2	$N_{-3}/N_5 \approx 13.6$
13	Pure nickel	Completely reversed bending	1.01×10^5 and 1.33×10^{-4}	Tests at 1089° K	$\epsilon_p = 1.6\%$	$N_{-4}/N_5 \approx 5$
13	Pure nickel	Completely reversed bending	1.01×10^5 and 1.33×10^{-4}	Tests at 1089° K	$\epsilon_p = 0.6\%$	$N_{-4}/N_5 \approx 0.3$
13	Age-hardenable Ni Ø nickel-chromium alloy	Completely reversed bending	1.01×10^5 and 1.33×10^{-4}	Tests at 1089° K	$\epsilon = 1.7\%$	$N_{-4}/N_5 \approx 15$
13	Age-hardenable nickel-chromium alloy	Completely reversed bending	1.01×10^5 and 1.33×10^{-4}	Tests at 1089° K	$\epsilon = 1.3\%$	$N_{-4}/N_5 \approx 4$
13	316 stainless steel	Completely reversed bending	1.01×10^5 and 1.33×10^{-3}	Tests at 1089° K	$\epsilon = 2.2\%$	$N_{-3}/N_5 \approx 21$
13	316 stainless steel	Completely reversed bending	1.01×10^5 and 1.33×10^{-3}	Tests at 1089° K	$\epsilon = 1.0\%$	$N_{-3}/N_5 \approx 4$
18	High-purity rolled lead strip	Completely reversed bending	1.01×10^5 and 6.67×10^{-1}		$\epsilon = 0.15\%$	$N_{-1}/N_5 \approx 7$
18	High-purity rolled lead strip	Completely reversed bending	1.01×10^5 and 6.67×10^{-1}		$\epsilon = 0.10\%$	$N_{-1}/N_5 \approx 19$
19	Aluminum - 4% copper alloy	Completely reversed bending	1.01×10^5 and 1.33×10^{-4}		$S = 184.8$ MN/m^2	$N_{-4}/N_5 \approx 4$
19	Aluminum - 4% copper alloy	Completely reversed bending	1.01×10^5 and 1.33×10^{-4}	Dry air at 1.33×10^{-4} N/m^2	$S = 184.8$ MN/m^2	$N_{-4}/N_5 \approx 9$
19	Aluminum - 4% copper alloy	Completely reversed bending	1.01×10^5 and 2.33×10^3	Wet air at 2.33×10^3 N/m^2	$S = 184.8$ MN/m^2	$N_3/N_5 \approx 0.6$

[a] Data obtained from Battelle Memorial Institute, Columbus, Ohio.

NASA-Langley, 1965 L-4084

NASA TN D-2563
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